

Hadronization of Dense Partonic Matter

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Abstract. The parton recombination model has turned out to be a valuable tool to describe hadronization in high energy heavy ion collisions. I review the model and revisit recent progress in our understanding of hadron correlations. I also discuss higher Fock states in the hadrons, possible violations of the elliptic flow scaling and recombination effects in more dilute systems.

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1. Introduction

Hadronization of partons is one of the unsolved problems in Quantum Chromodynamics (QCD). Hadronization is a non-perturbative process and deeply connected to confinement which by itself is still not understood on a fundamental level. Fortunately, techniques have been invented that help to deal with hadronization phenomena in elementary particle collisions in which hadrons are produced. They are based on universal parameterizations of the unknown non-perturbative quantities. A famous example are fragmentation functions $D_{a/A} \sim \langle 0|u|h(P)\rangle\langle h(P)|u|0\rangle$ which parameterize the probability that a hadron h with large momentum P is created from a parton u with momentum $p > P$ in the vacuum [1]. It has been shown that for hadron production at asymptotically large momentum transfer the cross section factorizes into a fragmentation function and a perturbative cross section between partons in a well-defined way. A second example are exclusive processes where the wave functions $\psi \sim \langle 0|uud|h(P)\rangle$ of the (few) lowest Fock states of a hadron appear [2].

Yet another method to deal with hadronization in a simplified way is the quark recombination model [3]. As in exclusive hadron production the matrix elements tested are of the same form as the one in exclusive processes $\sim \langle 0|uud|h\rangle$. This is only a formal correspondence, but attempts have been made to connect recombination to both fragmentation [4] and to exclusive hadron production [5].

Recombination can be directly applied to describe hadron production in rather dense parton systems [6, 7, 8, 9, 10, 11]. The motivation is twofold. First, there is an expectation that in a dense parton phase fragmentation is not the correct picture for hadron formation. Secondly, it became indeed clear that perturbative hadron production and fragmentation are not sufficient to explain RHIC data for hadrons at

transverse momenta of several GeV/c. This conclusion is mainly based on the observed large baryon/meson ratio [12], the nuclear modification factors R_{AA} (or R_{CP}) close to or above unity [12, 13, 14] and the remarkable scaling law for elliptic flow [15, 14].

2. Hadronization of Bulk Matter

In central heavy ion collisions a hot and dense fireball of deconfined quarks and gluons is created. In the recombination model one postulates the existence of thermalized parton degrees of freedom at the phase transition temperature T_c which recombine or coalesce into hadrons. It has been found to be sufficient to consider the lowest Fock state in each hadron, the valence quarks, which are given constituent masses around 300 MeV.

The spectrum of hadrons can be calculated starting from a convolution of Wigner functions [7]. For a meson with valence (anti)quarks a and b we have

$$\frac{d^3 N_M}{d^3 P} = \sum_{a,b} \int \frac{d^3 R}{(2\pi)^3} \int \frac{d^3 q d^3 r}{(2\pi)^3} W_{ab} \left(\mathbf{R} - \frac{\mathbf{r}}{2}, \frac{\mathbf{P}}{2} - \mathbf{q}; \mathbf{R} + \frac{\mathbf{r}}{2}, \frac{\mathbf{P}}{2} + \mathbf{q} \right) \Phi_M(\mathbf{r}, \mathbf{q}). \quad (1)$$

Here W_{ab} is the 2-particle Wigner function for partons a, b and Φ_M is the Wigner function of the meson. The sum runs over all possible parton quantum numbers. For simplicity the parton Wigner function is usually approximated by a product of single particle phase space distributions $W_{ab} = w_a w_b$. Several slightly different implementations of this formalism have been discussed in the literature [7, 8, 9]. See [10, 16] for earlier reviews.

In order to obtain an estimate when recombination is important as a hadronization mechanism, one can compare the yields of fragmentation and recombination starting from different parton spectra. Thermal parton spectra $w \sim e^{-P/T}$ play a special role. Recombination of thermal partons leads to an exponential hadron distribution with the same slope since

$$w_a w_b \sim e^{-xP/T} e^{-(1-x)P/T} = e^{-P/T}. \quad (2)$$

where x gives the momentum fraction of parton a . Therefore recombination is more effective than fragmentation on any thermalized parton ensemble. On the other hand one can show that a power-law parton spectrum favors fragmentation at least for large P_T , in accordance with perturbative QCD.

Eq. (1) does preserve momentum, but not energy. Therefore it can only be safely applied in a kinematic region where mass effects are small, i.e. for $P_T \gg M$. On the other hand fragmentation starts to dominate at very high P_T . The large jet quenching at RHIC further suppresses the contribution from fragmentation, so that recombination effects can be observed at intermediate P_T .

A very good description of hadron spectra and hadron ratios measured at RHIC can be achieved by combining hadron production from recombination for intermediate transverse momentum with a perturbative calculation using fragmentation and energy loss in the medium [6, 7]. Fig. 1 shows the P_T spectrum of π^0 , p , K_0^* and $\Lambda + \bar{\Lambda}$ in central Au+Au collisions obtained in [7]. The agreement with data is very good for $P_T > 2$ GeV/c. We note that the hadron spectra exhibit an exponential shape up to about 4 GeV/c for mesons and up to about 6 GeV/c for baryons, where recombination of thermal quarks dominates. Above, the spectra follow a power-law and production is dominated by fragmentation.

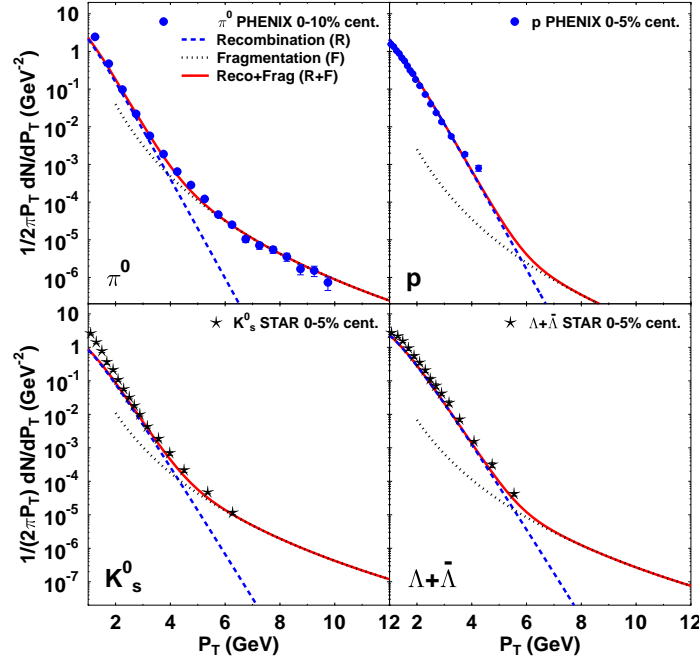


Figure 1. Spectra of π^0 , p , K_s^0 and $\Lambda + \bar{\Lambda}$ as a function of P_T at midrapidity in central Au+Au collisions at $\sqrt{s} = 200$ GeV [7]. Dashed lines are hadrons from recombination of the thermal phase, dotted line is pQCD with energy loss, solid line is the sum of both contributions. Data are from PHENIX (π^0 , p) [17, 12] and STAR (K_s^0 , $\Lambda + \bar{\Lambda}$) [13].

Let us now assume the parton phase exhibits elliptic flow $v_2^P(p_T)$. Recombination makes a prediction for elliptic flow of any hadron species after recombination [18, 7]:

$$v_2(P_T) = n v_2^P(P_T/n). \quad (3)$$

Here n is the number of valence quarks for the hadron. Note that this scaling law is derived using the assumption of infinitely narrow wave functions, such that the momentum is shared equally between the valence partons. Fig. 2 shows the measured elliptic flow v_2 for several hadron species in a plot with scaled axes v_2/n vs P_T/n . All data points (with exception of the pions) fall on one universal curve. This is an impressive confirmation of the quark scaling rule and the recombination model. The pions are shifted to lower P_T , because most pions in the detectors, even at intermediate P_T , are not from hadronization, but from secondary decays of hadrons. This together with allowing a finite width of the wave function can improve the description of the pion data [19].

The quark scaling of elliptic flow shows that the relevant degrees of freedom at early times in the collision are partons and they prove that these partons behave collectively.

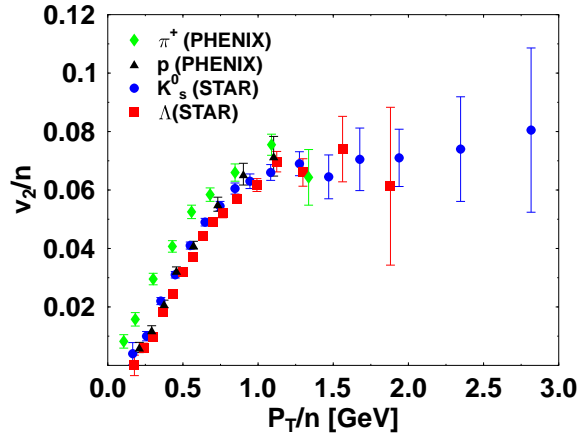


Figure 2. Elliptic flow v_2 for π^+ , p , K_0^s and Λ as a function of P_T scaled by the number of valence quarks n vs P_T/n . The data follows a universal curve, impressively confirming the quark scaling law predicted by recombination. Deviations for the pions are discussed in the text. Data are taken from PHENIX (π^+ , p) [15] and STAR (K_0^s , Λ) [14].

3. More on Elliptic Flow

The ϕ meson has long been discussed to provide a good test for the validity of the recombination model [20]. ϕ mesons are as heavy as protons and the questions is whether they follow the pattern of the other much lighter mesons, or whether they behave like protons and Lambdas. Data from RHIC now impressively confirm that the elliptic flow and nuclear modification factors of the ϕ are very similar to those for kaons [21]. This is another success for the recombination model.

Nevertheless one should ask to which accuracy one expects the scaling law for elliptic flow to hold. In particular, are the scaling factors of 2 and 3 indeed excluding any higher Fock states in the hadrons? A recent study found that higher Fock states in an expansion

$$|p\rangle = a_0|uud\rangle + a_1|uudg\rangle + \dots \quad (4)$$

could actually be accommodated [22]. It is easy to check that the hadron yields from a thermal parton spectrum do not change if additional partons are allowed to coalesce. Generally speaking the probability to form a cluster on n particles with fixed momentum P from a thermal bath is independent of n .

The situation changes for elliptic flow. Higher Fock states with n partons come with their own scaling factor n which seems to destroy the scaling with the number of valence quarks. However, under the assumption that the lowest Fock state is still dominating, the numerical effect of the corrections is surprisingly small. Fig. 3 shows the expected violation of the scaling law using the new asymmetry variable $A = (B - M)/(B + M)$ where B and M are the *scaled* elliptic flow of a meson and a baryon respectively [22]. One curve shows A for the lowest Fock state only and the other two correspond to hadrons which have a higher Fock state component with one additional parton with probability 30% and 50% respectively. Realistic wave functions

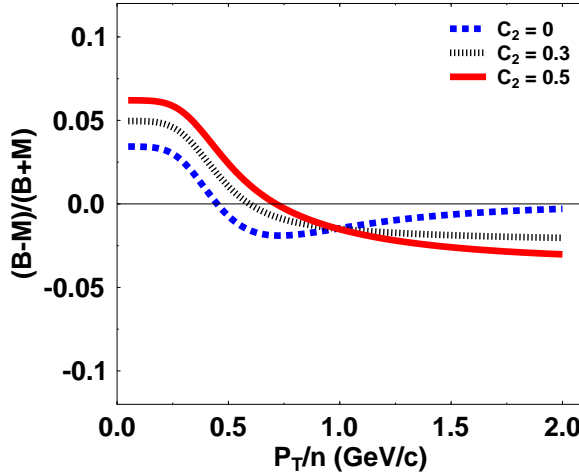


Figure 3. Scaling violation variable $A = (B - M)/(B + M)$ for three different probabilities C_2 to have an additional parton beyond the valence quark structure. Wave functions of finite width have been used which lead to a scaling violation even in the case $C_2 = 0$ of pure valence quark recombination [22].

with finite width have been used which leads to a scaling violation even for a pure valence quark configuration. Generally the violations are smaller than 5%. New data from STAR analyzes scaling violations in the data and finds them to have the predicted sign and order of magnitude [23].

The study did not specify the exact nature of the additional partons. They could be quark antiquark pairs or gluons. It was discussed for a long time what the fate of gluons in the recombination model is. One can argue that they have to dress the quarks just above the critical temperature. After this study it is clear that there is some room to accommodate gluons during the recombination process directly. Further investigations in this direction are necessary.

4. Hadron Correlations

More and more data on dihadron correlations are available from the RHIC experiments [24, 25]. The full picture shown by the data seems to be complicated and rich in detail. Before one can even begin to analyze the full data set there is one obvious question. The measurements find jet-like correlations at intermediate transverse momenta that seem to be coming from jet fragmentation rather than recombination. How can this be reconciled with the conclusion from single hadron measurements that recombination is the dominant source of hadrons in this kinematic regime?

Originally recombination was successfully applied to describe hadron spectra and elliptic flow starting from assumptions about the parton phase at hadronization. One crucial simplification always implemented is a factorization of any n -parton Wigner function into a product of independent single parton distributions

$$W_{1,\dots,n} = \prod_{i=1}^n w_i \quad (5)$$

By definition this factorization does not permit any correlations between partons. Consequently, no hadron correlations can emerge via recombination. It has to be emphasized that the above factorization was chosen for simplicity and it was justified because single inclusive hadron spectra could be described very well.

It has been shown in [26] that modifications of (5) including correlations between partons indeed lead to correlations between hadrons after recombination. The quality of the description of single hadron spectra does not suffer in the process. The source of jet-like correlations in the parton medium is the strong coupling of jets to the medium. The energy loss is estimated to be up to 14 GeV/fm for a 10 GeV parton [27]. This implies that most jets apart from those close to the surface are completely stopped, dumping their energy and momentum into a cell of about 1 fm³ in the rest frame of the medium. This results in a dramatic local heating, creating a hot spot in the fireball. Moreover, the directional information of the jet is preserved. Partons of such a hot spot exhibit jet-like correlations.

In [26] a simple extension of the correlation-free factorization (5) was considered (see also [28]). It is assumed that correlations are a small effect and that one can restrict them to 2-particle correlations C_{ij} . Then a 4-parton Wigner function can be written

$$W_{1234} \approx w_1 w_2 w_3 w_4 \left(1 + \sum_{i < j} C_{ij}\right). \quad (6)$$

The correlation functions C_{ij} between parton i and parton j can be arbitrary, but one assumes that they vary slowly with momentum and that they are only non-vanishing in a subvolume V_c of the fireball. A Gaussian ansatz $C_{ij} \sim c_0 e^{-(\phi_i - \phi_j)^2 / (2\phi_0^2)}$ seems to be reasonable to describe correlations in azimuthal angle. The 2-meson yield is given by a convolution of the partonic Wigner function W_{1234} with the Wigner functions Φ_A , Φ_B of the mesons with an additional integration over the hadronization hypersurface Σ [26]. It is assumed that the correlation strength $c_0 \ll 1$ which permits omitting quadratic terms like c_0^2 or $c_0 v_2$.

We can now study the associated yield Y_{AB} for a given trigger hadron A in a given kinematic window as a function of the relative azimuthal angle $\Delta\phi$ between the two. One finds

$$2\pi N_A Y_{AB}(\Delta\Phi) = Q \hat{c}_0 e^{-(\Delta\Phi)^2 / (2\phi_0)^2} N_A N_B. \quad (7)$$

The N_i are single particle yields in the kinematic window of the trigger meson or associated meson and $\hat{c}_0 = c_0 V_c / (\tau A_T)$ where τA_T is the hadronization volume. The factor $Q = 4$ (for two mesons) indicates an enhancement of the correlations in the hadron phase compared to the parton phase. The effect is the same as for the amplification of elliptic flow by the number n of valence quarks in the hadron. In the case of 2-parton correlations, Q counts the number of possible correlated pairs between the n_A (anti)quarks of meson A and the n_B (anti)quarks of meson B . In the weak correlation limit where quadratic terms are suppressed only single correlations are counted. Apparently one has

$$Q = n_A n_B, \quad (8)$$

thus $Q = 6$ for a meson-baryon pair and $Q = 9$ for a baryon-baryon pair.

Fig. 4 shows the associated yield of hadrons integrated in azimuthal angle around the near side ($\Delta\phi = 0$) for the case that the trigger is a baryon (proton or antiproton) and a meson (pion or kaon) for different centralities. The kinematic window is 2.5 GeV/ $c \leq P_{TA} \leq 4.0$ GeV/ c for trigger particles and 1.7 GeV/ $c \leq P_{TB} \leq 2.5$ GeV/ c

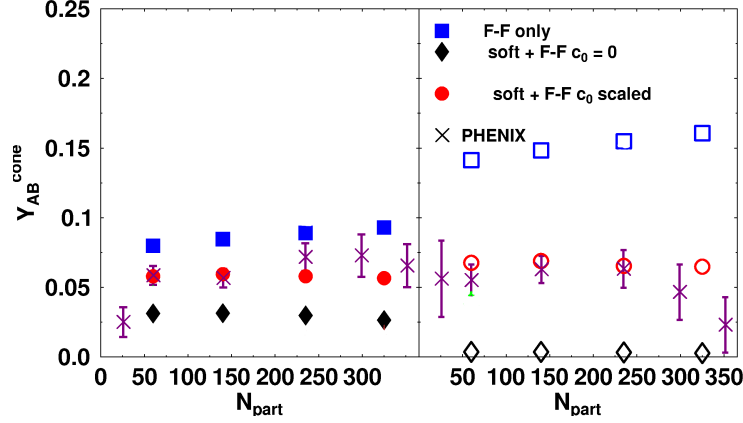


Figure 4. The associated yield Y_{AB}^{cone} for baryon triggers (right panel) and meson triggers (left panel) as a function of N_{part} . Squares: fragmentation only; diamonds: fragmentation and recombination with $\hat{c}_0 = 0$; circles: the same with $\hat{c}_0 = 0.08 \times 100/N_{part}$; data: PHENIX [25].

for associated particles, and $|y_A|, |y_B| < 0.35$. Fig. 4 shows the associated yield with only fragmentation, and fragmentation and recombination both taken into account together with PHENIX data [25]. A good description of the data can be reached assuming a constant correlation volume. The parameters used for the fireball are the same that lead to a good description of single hadron spectra and elliptic flow [7].

5. Soft-Hard Recombination

Some implementations of recombination take into account the possibility that hard partons can recombine with soft partons [8, 29]. This soft-hard recombination smoothenes the transition between the pure fragmentation and pure (thermal) recombination regions. It was predicted that typical recombination features like a larger baryon/meson ratio would then extend to even higher P_T , beyond 6 GeV/ c . Indeed such behavior might have been seen in recent data [30].

Soft-hard recombination could be a correction to fragmentation which is even important in much more dilute systems. The reason is that fragmentation is an extremely ineffective mechanism to create baryons. Soft-hard recombination is a very good candidate to explain the very larger Cronin enhancement for baryons in $d+Au$ collisions [31]. There is no thermal parton phase created in $d+Au$ collisions, but the existence of a cloud of soft partons with exponential spectrum is sufficient to boost baryon production via coalescence. Soft-hard recombination could even be responsible for the suppression of hadrons at forward rapidities in $d+Au$ [32].

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References

- [1] Collins J C and Soper D E 1982 *Nucl. Phys. B* **194** 445
- [2] Chernyak V L and Zhitnitsky A R 1977 *JETP Lett.* **25** 510
Efremov A V and Radyushkin A V 1980 *Phys. Lett. B* **94** 245
- [3] Das K P and Hwa R C 1977 *Phys. Lett. B* **68** 459
Erratum *ibid.* **73** 504
- [4] Migneron R, Jones L M and Lassila K E 1982 *Phys. Lett. B* **114** 189
- [5] Ochiai T 1986 *Prog. Theor. Phys.* **75** 1184
- [6] Fries R J, Müller B, Nonaka C and Bass S A 2003 *Phys. Rev. Lett.* **90** 202303
Fries R J, Müller B, Nonaka C and Bass S A 2003 *J. Phys. G: Nucl. Part. Phys.* **30** 223
Nonaka C, Fries R J and Bass S A 2004 *Phys. Lett. B* **583** 73
- [7] Fries R J, Müller B, Nonaka C and Bass S A 2003 *Phys. Rev. C* **68** 044902
- [8] Greco V, Ko C M and Levai P 2003 *Phys. Rev. Lett.* **90** 202302
Greco V, Ko C M and Levai P 2003 *Phys. Rev. C* **68** 034904
- [9] Hwa R C and Yang C B 2003 *Phys. Rev. C* **67** 034902 Hwa R C and Yang C B 2003 *Phys. Rev. C* **67** 064902
- [10] Fries R J 2004, *J. Phys. G: Nucl. Part. Phys.* **30** 853
- [11] Fries R J 2005 *J. Phys. G: Nucl. Part. Phys.* **31** 379
- [12] Adcox K *et al* (PHENIX Collaboration) 2002 *Phys. Rev. Lett.* **88** 242301
Adler S S *et al* (PHENIX Collaboration) 2003 *Phys. Rev. Lett.* **91** 172301
Adler S S *et al* (PHENIX Collaboration) 2004 *Phys. Rev. C* **69** 034909.
- [13] Long H (STAR Collaboration) 2004 *J. Phys. G: Nucl. Part. Phys.* **30** 193
- [14] Adams J *et al* (STAR Collaboration) 2004 *Phys. Rev. Lett.* **92** 052302
- [15] Adler S S *et al* (PHENIX Collaboration) 2003 *Phys. Rev. Lett.* **91** 182301
- [16] Fries R J (2004) *Continuous Advances in QCD* ed T Gherghetta (World Scientific 2004) 203
Fries R J 2005 *J. Phys. Conf. Ser.* **9** 290
- [17] Adler S S *et al* (PHENIX Collaboration) 2003 *Phys. Rev. Lett.* **91** 072301
- [18] Voloshin S A 2003 *Nucl. Phys. A* **715** 379
Lin Z W and Ko C M 2002 *Phys. Rev. Lett.* **89** 202302
Molnar D and Voloshin S A 2003 *Phys. Rev. Lett.* **91** 092301
- [19] Greco V and Ko C M 2004 *Phys. Rev. C* **70** 024901
- [20] Nonaka C, Müller B, Asakawa M, Bass S A and Fries R J (2004) *Phys. Rev. C* **69** 031902
- [21] Pal D (PHENIX Collaboration) 2005 *Preprint* hep-ex/0510020
Cai X Z (STAR Collaboration) 2005 *Preprint* nucl-ex/0511004
- [22] Müller B, Fries R J and Bass S A 2005 *Phys. Lett. B* **618** 77
- [23] Sorensen P R (STAR Collaboration) 2005 *Preprint* nucl-ex/0510052
- [24] Adler C *et al* (STAR Collaboration) 2003 *Phys. Rev. Lett.* **90** 082302
- [25] Adler S S *et al* (PHENIX Collaboration) 2005 *Phys. Rev. C* **71** 051902
Sickles A (PHENIX collaboration) 2004 *J. Phys. G: Nucl. Part. Phys.* **30** 1291
- [26] Fries R J, Bass S A and Müller B 2005 *Phys. Rev. Lett.* **94** 122301
- [27] Wang X N 2004 *Phys. Rev. C* **70** 031901.
- [28] Fries R J 2005 *J. Phys. Conf. Ser.* **27** 70
Bass S A, Fries R J and Müller B 2005 *Preprint* nucl-th/0510084
- [29] Hwa R C and Yang C B 2004 *Phys. Rev. C* **70** 024904
Hwa R C and Yang C B 2004 *Phys. Rev. C* **70** 024905
- [30] Adams J *et al* (STAR Collaboration) 2006 *Preprint* nucl-ex/0606003
- [31] Hwa R C and Yang C B 2004 *Phys. Rev. Lett.* **93** 082302
Hwa R C and Yang C B 2004 *Phys. Rev. C* **70** 037901
- [32] Hwa R C, Yang C B and Fries R J 2005 *Phys. Rev. C* **71** 024902
Fries R J 2005 *AIP Conf. Proc.* **792** 299